PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Improvements in or relating to Ionisation Chamber Circuits

We, UNITED KINGDOM ATOMIC ENERGY AUTHORITY, London, a British Authority, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to radiation measuring apparatus employing alternating polarising potentials on ionisation chambers.

When ionisation chambers are used in the conventional manner for the measurement of ionising radiations it is usual to apply a D.C. polarising potential to the chamber sufficient to ensure almost complete collection of ions and to measure the resulting direct current obtained through the chamber. In nuclear reactor instrumentation practice these currents normally lie within the range 10^{-12} to 10^{-3} amps.

The measurement of small direct currents presents certain problems, typically those associated with drift in the measuring equipment, and relatively complex circuits are needed if these difficulties are to be avoided. One widely used method is to convert the direct current to an alternating signal in a low-drift modulator before the measuring processes are carried out, since a high degree of amplification is readily achieved with a minimum of drift using A.C. techniques. The present invention is concerned wtih eliminating the D.C. entirely and causing the ionisation chamber to originate an alternating current signal.

Such a scheme offers additional advantages since, if phase-sensitive measuring equipment is used, a high degree of failure to safety can result and the capacitive component of current through the ion chamber can provide a self-monitoring facility. This latter feature assumes much importance in nuclear reactor instrumentation, especially in shut-down circuits, and is already taken advantage of in some circuit designs by providing a small A.C. modulation on the ion chamber D.C. polarising potential.

This advantage, together with the inherent simplicity and fail-to-safety character of an A.C. operated system, can make such a scheme desirable even where low current measurement is not required, e.g. shut-down channels for nuclear reactors.

According to one aspect of the present invention radiation measuring apparatus comprises an ionisation chamber, an A.C. generator for providing a polarising potential for the chamber, an A.C. amplifier for measuring the chamber-current, phase-sensitive means for utilising the in-phase or anti-phase component of amplifier output as a measure of radiation flux, and phase-sensitive means for utilising the quadrature component of amplifier output to check that the apparatus is functioning properly.

According to another aspect of the present invention radiation measuring apparatus comprises an A.C. voltage generator providing in-phase and anti-phase outputs, an ionisation chamber connected between the in-phase output and the input of an A.C. summing amplifier, said generator being adapted to apply to the chamber an A.C. polarising potential sufficiently low to make the chamber a substantially linear circuit element, a resistor connected between the anti-phase output and the input of the summing amplifier, and phase-sensitive means for utilising the in-phase or anti-phase component of amplifier output as a measure of radiation flux.

The resistor may be set to provide an anti-phase current equal in amplitude to a predetermined level of in-phase chamber current, there being provided phase-sensitive relay means controlled by the amplifier output such that the relay means operates if the in-phase chamber current reaches or exceeds the given value. The apparatus may also comprise phase-

$$i \propto \left[\frac{d(N)}{dt} \right]^{0.6}$$

for both D.C. and A.C. voltages up to 1 volt r.m.s.

When X is large the relationship between X and i becomes non-linear, i tending to become independent of X as the field is increased, representing saturation conditions. Under these conditions i tends to become proportional to the ion production rate (or flux). The results described above confirm that this also applies to the A.C. case.

Thus the "saturated" condition provides a signal, rich in harmonics, more or less independent of the applied potential peak amplitude and with a fundamental component which is proportional to neutron flux. The capacitance component of current is high and the ionisation current is the maximum obtainable for a given set of chamber conditions.

The "unsaturated" condition gives a relatively pure sinusoidal output, proportional to the amplitude of the applied potential over a small range, i.e. the chamber behaves as a linear circuit element, and with a fundamental component approximately proportional to the square root of neutron flux. The capacitance component of current is much reduced compared with the "saturated" case whilst the ionisation current is reduced to lesser extent. Both conditions of operation give rise to a fundamental component whose phase loads somewhat on that of the applied potential, due to the electron and ion spikes, even with low amplitudes, since these effects can never be completely absent.

A.C. operation has one application in reactor shut-down channels. An important feature of a shut-down system is the stability of the trip level. It has been shown above that two modes of A.C. operation can be distinguished—operation above or operation well below saturation levels causes the ionisation chamber to approximate to a linear circuit component, it is possible to determine the trip point by arranging the ionisation chamber in a bridge-type circuit which can be adjusted to give a null for in-phase components at the required flux level. Thus the trip level becomes dependent only on the circuit components, accurate stabilisation of the applied potential is not necessary and the output waveform is free from harmonics. The required level of polarising potential is low (probably less than 1 volt peak) and this can be advantageous in circuit design. While operation at voltages above saturation is possible, the non-linearity of the chamber under these conditions and the high potential required are obvious disadvantages.

The presence of the electron and ion "spikes" is not important provided that the measuring circuit can distinguish the in-phase or anti-phase component of current.

The resistance of the boron coatings on the ionisation chamber electrodes is of such an order that, at currents of 10^{-7} amps, some effect on the resultant current will be observed when the applied voltages are below one volt, owing to the voltage drop in the coating. If this resistance were stable the final result would be to cause a deviation in the flux/current law at currents of this order. The instability of the coating resistance makes this deviation unpredictable and, for this reason, it is preferred to short-circuit the boron coating by applying thereto a conducting coating which is electrically connected to the electrode. This can be done by sputtering aluminium on to the surface of the boron, the boron coating being removed from a large number of small areas of the electrode so that good electrical contact is made between the sputtered film and the electrode.

Fig. 9 shows a preferred arrangement, in block schematic form, in which the ion chamber is used in the linear (low voltage) regime.

In this arrangement a signal of one volt or less is applied to the polarising electrode of the chamber 1 at a frequency in the region of 60 c/s. This supply is derived from an oscillator 2 giving a push-pull output so as to provide an anti-phase current at a summing junction 3 of amplitude determined by the variable resistor R.

The chamber 1, resistor R, and the twin output circuits of the generator 2 thus form the four arms of a bridge-type circuit, the amplifier 4 being in effect connected across the bridge between the common terminal of the twin output circuits (normally earth) and the junction of chamber 1 and resistor R.

The value of resistor R is set to provide a null at the summing junction for in-phase components of current when the chamber current reaches that value corresponding to a pre-determined shut-down neutron flux level. If the chamber current exceeds this value the phase at the junction reverses. The output of the summing amplifier 4, which is of the virtual-earth type, supplies a phase-sensitive meter 5 which indicates the resultant in-phase component amplitude. This meter is provided with an offset zero (representing the shut-down level) and is calibrated to read % deviation (plus or minus) from shut-down. It can be shown that the power law relating flux and current in an ionisation chamber operating in the linear regime makes calibration of this type most convenient.

At this point in the circuit a phase-sensitive relay 6 is connected sensitive to the quadrature component of current, so as to provide a monitor alarm on the capacitance current originating in the chamber. This alarm oper-

desirable even where low current measurement is not required, e.g. shut-down channels for nuclear reactors.

In the accompanying drawings,

Figs. 1—4 are waveforms of the currents produced in an ionisation chamber using a sinusoidal polarising potential under various conditions.

Figs. 5(a), (b) and (c) are curves of ionisation current against sinusoidal polarising potential.

Fig. 6 is an equivalent circuit diagram of a boron-coated ionisation chamber.

Fig. 7 is a waveform of the current produced in an ionisation chamber using a square-wave polarising potential.

Fig. 8 is a circuit diagram of a reactor trip circuit.

Figs. 1 and 2 indicate qualitatively the general shape of current waveform obtained from sinusoidal applied potentials in two extreme cases: (a) where the applied peak alternating potential is very much greater than the corresponding D.C. saturation potential for the particular set of conditions (Fig. 1); and (b) where the applied peak alternating potential is very small (Fig. 2). The capacitance component of current has, in both cases, been effectively balanced out. For intermediate values of applied potential the waveforms exhibit characteristics which are recognisable as being intermediate between the two extremes.

The waveform of Fig. 1 requires some explanation and a theoretical study together with further experimental work has shown that this behaviour may be accounted for by the following, somewhat simplified, explanation.

During a finite period when the applied potential is close to zero very little current will be collected and the density of positive ions and negative electrons (assuming no electron attachment) will build up towards a value determined by the rate of ion pair production, by the value of the recombination coefficient and by the effects of diffusion to the walls of the chamber. As the applied potential rises, free electrons, which have a high mobility as compared with the +ve ions, will contribute to a rapid rise in collection current, even when the applied potential is still quite low (below 1 volt) but very shortly after this the consequent reduction of electron density together with the effects of space charge build up may be expected to result in a reduced current from this cause despite the steady increase in applied potential.

When the applied potential reaches a value at which appreciable drift velocities are produced in the positive ions a similar sequence of events may be expected to occur with these particles and finally a steady current is obtained, being the saturation current, which exists throughout the period during which the applied potential exceeds the saturation value and is nearly independent of the magnitude of this potential. It is convenient to refer to the two bumps in the waveform thus obtained as the "electron spike" and the "ion spike."

Because of the non-linear tendencies indicated by these results, care has to be exercised in the interpretation of output current measurements. Measurements made have comprised a record of the current waveform, measurements of the inphase and quadrature components of fundamental frequency relative to the applied potential, and a measurement on a peak-reading valve voltmeter. This latter measurement is of doubtful value for those cases where the waveform is significantly distorted.

Examples of the way in which these measurements vary with applied voltage are shown in Figs. 5(a), (b) and (c) for an air-filled chamber having boron-coated electrodes in a thermal neutron flux, using the (n,α) reaction with boron 10.

Conclusions in the General Case

An approximate expression for the collection current resulting from a given D.C. applied potential (neglecting space-charge effects) is given by:

$$i = \frac{e(K^{+}+K^{-})^{2}X^{2}}{2pd}\left[\left\{1+\frac{4pd^{2}\frac{d(N)}{dt}}{(K^{+}+K^{-})^{2}X^{2}}\right\}^{1/2}-1\right]$$

Where

i = current density (e.s.u.)
e = electronic charge (e.s.u.)
p = recombination coefficient
K = charge mobility (e.s.u.)
d = electrode spacing (cms.)
X = field strength (e.s.u.)
$\frac{d(N)}{dt}$ = ion production rate (pairs/sec/cc.)

This expression cannot be used to obtain the collection current when X is a time varying function, but is useful as a guide to some of the effects which may be expected. In particular, it may be noted that when X is small a nearly linear relationship exists between X and i. The relationship between i and ion production rate (which is proportional to flux) approaches a square root law as X tends to zero.

When X is large the relationship between X and i becomes non linear, i tending to become independent of X as the field is increased, representing saturation conditions. Under these conditions i tends to become proportional to the ion production rate (or flux). It might be expected that these general conclusions could

only assume significantly large values (0.1μF and 10mV) in the presence of water vapour, and that these conclusions might have been expected from the known properties of materials of this sort.

The reduction of amplitude of the electron spike by the boron coating arises as a result of its resistance to current flow. The mechanism may be explained as follows: —

When the electron spike normally occurs the applied potential is in the millivolt region. The resistance of the boron coatings are of such an order that the currents corresponding to the electron spike would, in flowing through a resistor of this value, also produce potential differences in the millivolt range. The effect is thus to severely attenuate the amplitude of current which can flow. In the case of the ion spike, the applied potential is now several volts although the current is not significantly greater. Thus the small voltage developed across the resistance of the boron coating has little or no effect upon the ion spike. If the coating exhibits sufficient capacity the electron spike will be restored.

These conditions have been reproduced using real resistors and capacitors in series with the ionisation chambers so it seems likely that the observed effects can be satisfactorily explained in this way.

Another effect, for which an explanation had to be found, occurred when air was used as a gas filling. In this case no electron spike would be expected in view of the electro-negative characteristic of oxygen. However, although this was found to be true in the initial stages of an experiment it was noted that an electron spike would develop after prolonged irradiation in thermal neutron fluxes. (10^{15} n.v.t.). It seems likely that this effect may be attributed to the chemical changes which occur in air under irradiation and this is supported by the results of a mass spectrographic analysis of air taken from two chambers irradiated for two weeks in a flux of 10^{10} (Table 2) and by calculations carried out to determine the rate of change of oxygen concentration in air under irradiation. The gas formed by the compositions given in Table 2 would certainly be expected to show the electron "spike" phenomena.

TABLE 2

Mass spectrographic analysis of samples of air after two weeks irradiation at a flux of 10^{10} n/cm^2/sec.

Sample	Nitrogen	Oxygen	Argon	Nitrogen Oxides	CH_4
A	87.3%	3.09%	1.12%	8.01%	0.47%
B	88.1%	3.1%	1.4%	6.95%	0.44%

Finally, a further effect which has been noted was a tendency after a rapid growth in the amplitude of the electron "spike" (where one exists) in the first few minutes after irradiation. In fluxes of 10^8 n/cm^2/sec a period of about 10 minutes was required for the effect to be complete and the phenomena showed signs of being reversible in that the process could be repeated if the chamber were first removed from the neutron source for a short period. This phenomena has not been fully explained, but it is suggested that it could be attributed to changes in the electrical behaviour of the boron coatings under irradiation.

Choice of gas filling

The need for nuclear and chemical compatibility of the filling gas in the proposed environment restricts the range of suitable gases and most of the experimental investigations were carried out with gases which appeared to meet these requirements.

Although air was used in some of the earlier experiments this type of filling is not compatible with high neutron fluxes in an enclosed aluminium vessel but was used, in the first instance, as an experimental convenience and, later, in order to investigate the phenomena of oxygen depletion described above.

Hydrogen and helium have been used in the experiments and both these gases appear to have attachment coefficients which are very sensitive to the presence of impurities so that the value of these gases as a filling depends upon the importance to be attached to the electron "spike" phenomenon. It seems likely that the main requirement should be that this phenomenon be stable and this may be difficult to ensure if very high degrees of purity are required. Alternatively, if stability is to be achieved by doping with a suitable impurity, it will be necessary to be certain that changes cannot occur under irradiation and this matter deserves further investigation.

Nitrogen appears to have a low attachment coefficient and to be relatively insensitive to impurities, behaving in a highly stable manner. Objections to the use of nitrogen can be raised on the grounds of enhanced chemical activity in high radiation fluxes.

Argon behaves in a manner similar to nitrogen and its chemical inertness is an advantage which makes it attractive for use in this application.

Oxygen has a high attachment coefficient for electrons and this suppresses the electron "spike," but oxygen is unsuitable chemically as a filling gas, mainly due to its reaction with aluminium in high levels of flux.

Boron trifluoride appears to present some advantages as a filling gas in that the boron coatings are eliminated. In practice it would seem that the chemical activity of this gas results in the development of a film on the

extent since the difficulties of amplification increase rapidly below a few cycles per second. It may be possible to take advantage of the "resonance" phenomenon described previously and thereby to increase the in-phase component of current, but it appears that this effect is likely to be most pronounced at the higher operating frequencies and is not, therefore, consistent with low capacitance currents.

Application to Measurement of High-Flux Levels

As already outlined A.C. operation appears to be attractive for reactor shutdown channels. Before considering possible circuit techniques, it is desirable to note how some of the observed effects may influence the system design.

An important feature of a shutdown system will be the stability of the trip level. It has been shown that two modes of A.C. operation can be distinguished — operation above or operation well below saturation level. Since operation well below saturation levels causes the ionisation chamber to approximate to a linear circuit component, it becomes possible to determine the trip point by arranging that the ionisation chamber forms parts of a bridge adjusted so as to give a null for in-phase components at the required flux level. Thus the trip level becomes dependent only on the bridge circuit components, accurate stabilisation of the applied potentials is not necessary and the output waveform is free from harmonics. The required level of polarising potential is low (probably less than 1 volt peak) and this may have some advantage in circuit design. Whilst operation at voltages above saturation should not be excluded, the non linearity of the chamber under these conditions and the high potential required are obvious disadvantages.

Effect of Electron and Ion "Spikes"

Since the presence of the ion and electron "spikes" can be regarded as evidence of non-linearity in the ion chamber and since the electron "spike" is produced at applied potentials in the millivolt range, it has been argued that the presence of such a spike when medium voltages are applied (say 10 volts) is evidence of considerable non-linearity at much lower voltages. Experiment indicates that this is only partly true and it would appear that the only major effect is a small phase advance, the non-linearity being much reduced by virtue of space charges. This may be inferred from the D.C. saturation curves which do not show any marked difference in degree of linearity with applied voltage, when this voltage is low, between chambers filled with high or low electron attachment coefficient gases. Thus, although "saturation" for electrons occurs in the millivolt range for typical operation condition no deviation from linearity is observed in this region as a result of the build-up of space charges.

From these conditions it would appear that no great importance need be attached to the presence of these "spikes" provided that the measuring circuit can distinguish the in-phase component of current, so that whilst it may be desirable to find a gas filling which prevents the production of an electron "spike," it is not essential to do so.

Influence of the Boron Coating

Experimental results indicate that the effects described due to the boron coating may be somewhat unstable. The resistance of the boron film is of such an order that, at currents of 10^{-7} amps, some effect on the resultant current will be observed when the applied voltages are below one volt. If this resistance were stable the final result would be to cause a deviation in the flux/current law at currents of this order. The instability of the coating resistance would make this deviation unpredictable and, for this reason, the described technique whereby the boron film is short circuited, would appear to be a necessary precaution.

Circuit Arrangements

A great number of variations in circuit design are possible. One proposal is shown in block schematic form in Fig. 18, in which the ion chamber is used in the linear (low voltage) regime.

In this proposal a signal of one volt or less is applied to the polarising electrode of the chamber at a frequency in the region of 60 c/s. This supply is derived from an oscillator giving a push-pull output so as to provide an anti-phase current at a summing junction of amplitude determined by the resistor R in Fig. 8. The value of this resistor is set so as to provide a null at the summing junction for in-phase components of current when the chamber current reaches that value corresponding to a pre-determined neutron flux level. The output of the summing amplifier supplies a phase sensitive meter which indicates the resultant in-phase component amplitude. This meter is provided with an offset zero (representing the shutdown level) and is calibrated to read % deviation (plus or minus) from shutdown. It can be shown that the power law relating flux and current in an ionisation chamber operating in the linear regime makes calibration of this type most convenient.

At about this point in the circuit a phase-sensitive relay can be connected sensitive to the quadrature component of current, so as to provide a monitor alarm on the capacitance current originating in the chamber.

Further amplification of the signal and connection to a phase sensitive trip relay, operating on the in-phase component of current, will provide a trip facility and should be designed to operate within about 0.5% of shutdown.

An arrangement, somewhat similar in principle, is possible in which square wave

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1 SHEET

This drawing is a reproduction of the Original on a reduced scale.

FIG. 9.

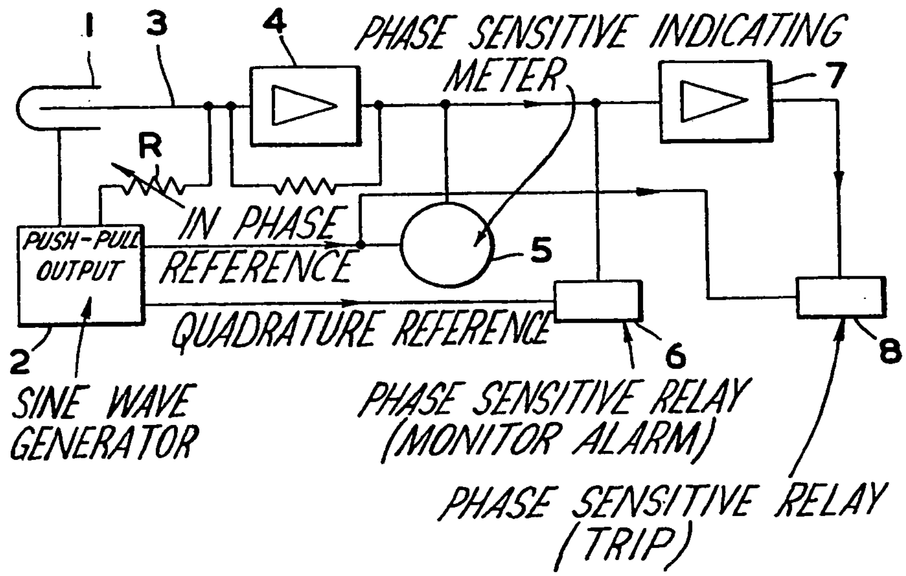

FIG. 5a.

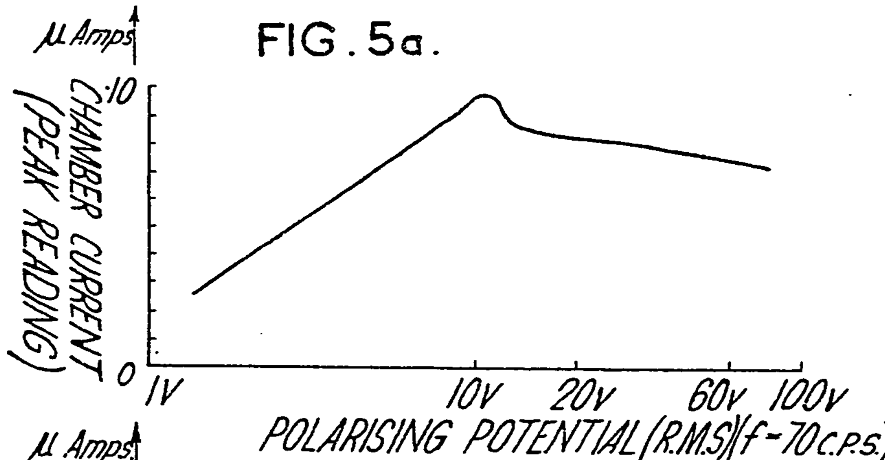

FIG. 5b.

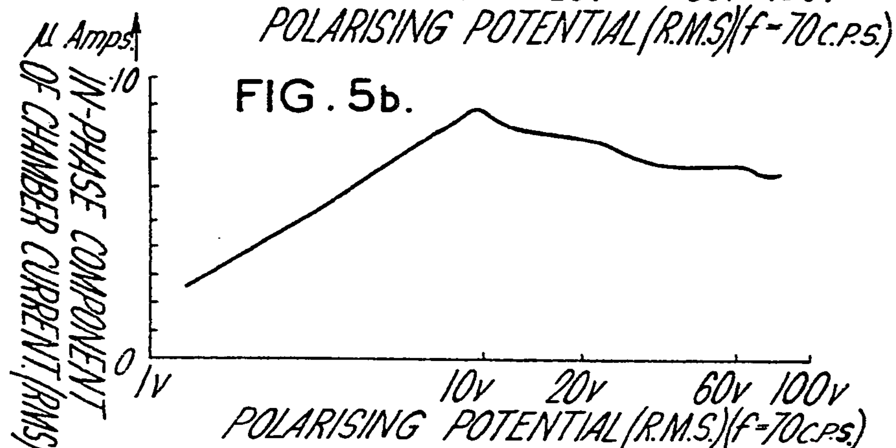

FIG. 5c.

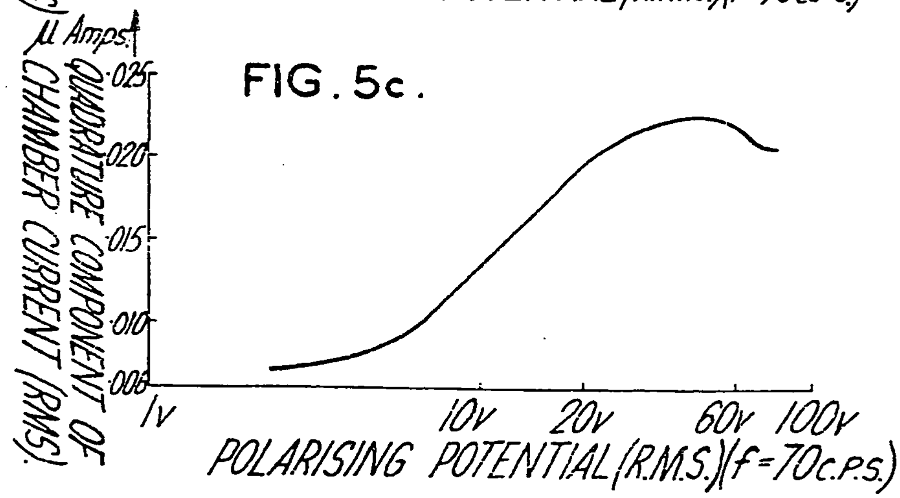

FIG. 5a.

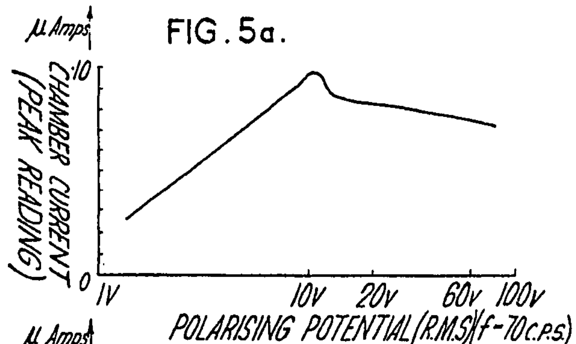

FIG. 5b.

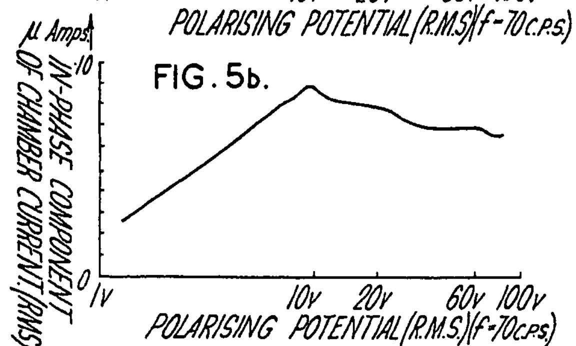

FIG. 5c.

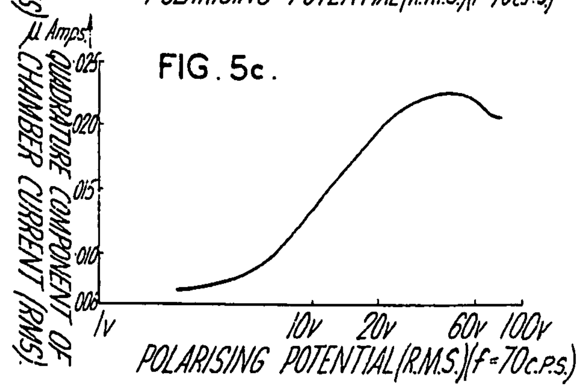

FIG. 6.

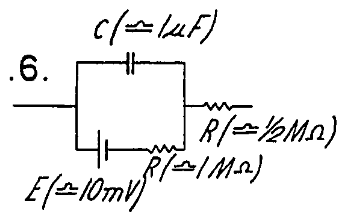

FIG. 7.

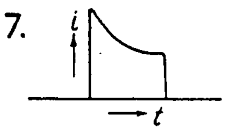

FIG. 8.